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ELECTROFLUIDMECHANICS: A STUDY OF ELECTROKINETIC ACTIONS IN FLUIDS

HENRY R. VELKOFF

TECHNICAL REPORT No. ASD TR 61-642

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PROPULSION LABORATORY
AERONAUTICAL SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

Project No. 3141

Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio.
Rpt No. ASD-TR-61-642. ELECTROFLUID-MECHANICS: A STUDY OF ELECTROKINETIC ACTIONS IN FLUIDS. February 1962, 51 p. incl illus and tables.

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been observed. A significant body force can be exerted on either an ionized fluid or a neutral nonionized fluid. Since the application of electric fields to fluids may strongly affect heat transfer or the fluid boundary layer, the field of electro-fluidmechanics may take its place with magneto-hydrodynamics as an important physical phenomena.

1. Electrostatic Fields
2. Fluid Mechanics
3. Heat Transfer
4. Hydrodynamics
5. Boundary Layer

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FOREWORD

This report was prepared by the Propulsion Laboratory, Directorate of Aeromechanics, Deputy for Technology, Aeronautical Systems Division, with Henry R. Velkoff acting as project scientist. The work reported herein was accomplished under Project Number 3141, "Electric Propulsion Technology."

The author wishes to express his appreciation to Professor S. M. Marco of The Ohio State University and Mr. Eric Soehngen of the Aeronautical Research Laboratory for their guidance and encouragement in the conduct of this research. The work of Mr. James Clark of the Flight Dynamics Laboratory served as a strong impetus to this study. His work became available for review at about the time that the full significance of the electrofluid interactions was grasped. His test results forcefully demonstrated that the interactions could not only be observed, they could be controlled.

This report covers the introductory portion of the phased study of electrokinetics in fluid motion. Subsequent work will concern itself with experimental studies and analytical correlations. This report covers the work accomplished from April through July 1961.

ABSTRACT

The possible interactions between electric fields and fluids are reviewed. Many actions are found to exist, and the basis for many of the actions is discussed. The study indicates that a wide range of electrofluidmechanic phenomena have actually been observed. A significant body force can be exerted on either an ionized fluid or a neutral nonionized fluid. Since the application of electric fields to fluids may strongly affect heat transfer or the fluid boundary layer, the field of electrofluidmechanics may take its place with magnetohydrodynamics as an important physical phenomena.

PUBLICATION REVIEW

This technical report has been reviewed and is approved.

FOR THE COMMANDER:

R. E. SUPP
Chief, Electric and Advanced
Propulsion Branch
Propulsion Laboratory

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LIST OF SYMBOLS

$\bar{a}$ = unit vector

B = magnetic flux density

$\bar{c}$ = mean velocity of molecules

D = electric flux density

D_i = coefficient of diffusion

E = electric field strength

e = unit charge (charge of electron)

F = force

g = gravitational constant

H = magnetic field

J = current density

K = ion mobility

k = Boltzmann's constant

L = mean free path

ℓ = length in dipole

m = mass of molecule or ion

n_i = number of ions per unit volume

P = polarization (dipole moment per unit volume)

p = dipole moment

q = charge

r = distance along a radius

t = time

V = voltage (potential difference)

V_d = double-layer potential

v = velocity

z = valency of atom

LIST OF SYMBOLS (Continued)

α_i = coefficient of recombination

γ = specific weight

δ = double-layer thickness

ϵ_o = permittivity of free space

ϵ = permittivity of substance

ζ = zeta potential

η = polarizability of a molecule

μ = viscosity

ρ = charge density

σ = surface charge density

ω = frequency of alternating field

INTRODUCTION

The influence exerted by an electric field on gases and liquids has been known for many years. Primary attention was given to electrolytic phenomena and to gas discharges. Relatively little work, however, was done on the effects of electric fields acting alone on the flow of fluids. Such field effects tend to be rather subtle in contrast to the relatively large fluid body force generated by the interaction of an electric field and a transverse magnetic field. This latter fluid-electromagnetic interaction gives rise to the whole field of magnetohydrodynamics (MHD). The interest in MHD has received wide attention in recent years because of potential applications in power generation, controlled fusion, and space propulsion. The subtle electric field effects, however, merit consideration apart from the mass of the work done on magnetohydrodynamics. The fluid-electric interactions are generally distinct from those in the MHD field.

An electric field can influence not only fluids containing charged particles and conducting fluids, but neutral nonconducting fluids as well. This wide range of action may provide controllable body forces within the fluid without the high degree of ionization customarily used in magnetohydrodynamics. Changes in fluid properties, such as viscosity or conductivity, can also occur in the presence of a field, and thus the entire behavior of fluid flow and heat transfer may be affected.

It is the purpose of this research to explore the possible interactions between electric fields and fluids, select one of the many possible interactions, and study this one both analytically and experimentally. Because of the scope of the interactions, an over-all survey will be undertaken including descriptions, explanations when available, and analytical expressions where possible. The range of possible effects on fundamental fluid behavior and heat transfer will then be outlined and discussed.

Manuscript was released by the author for publication as an ASD Technical Report on 15 November 1961.

INTERACTIONS OF ELECTROMAGNETIC FIELDS

FUNDAMENTAL INTERACTIONS

The fundamental forces available are electrical in nature. To properly orient later discussion, both electric and magnetic effects will be reviewed briefly.

Electrostatic Influence

A fundamental concept in electricity is that of Coulomb's law of repulsion between two charged particles of like sign.

$$\bar{F} = \frac{q_1 q_2}{4 \pi \epsilon r^2} \bar{a} \tag{1}$$

where:

$\bar{F}$ = force,

q_1, q_2 = charge,

ϵ = permittivity (dielectric constant),

r = distance between charges, and

$\bar{a}$ = unit vector.

This relationship leads to the concept of the electric field, or force per unit charge, $F = qE$, where E is the electric field strength. The simplest action of an electric field is that of the force induced on a charged particle placed in that field. Particles that can be influenced in this manner are electrons, positive and negative ions, and a whole host of macroscopic particles. Typical macroscopic particles are charged dust particles, droplets of liquid, impurities in solutions, colloids, or any other aggregations that can sustain an electrical charge. Although the magnitude of the action for the various particles may be different, the basic motion is that of the drift of the charged particle as a result of the force induced by the electric field, as shown in Figure 1.

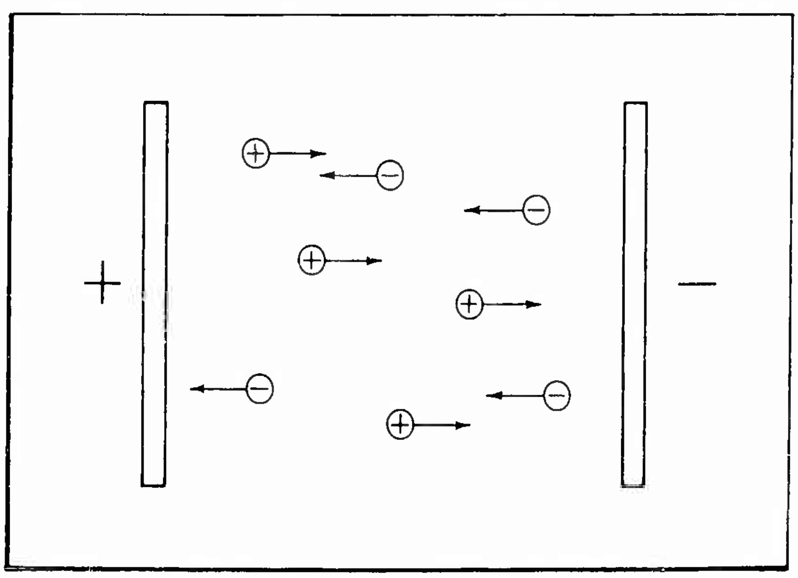


Figure 1. Drift of ions in a uniform field

In contrast to this simple Coulomb attraction is the subtle influence of the electric field on neutral molecules. The action of polarization in a dielectric illustrates this phenomenon. When an ideal nonconducting dielectric is placed between the plates of a charged condenser, the theory of dielectric action indicates that a change occurs in the electrical orientation of the molecules. A slight displacement of the positive and negative charge within the molecules is induced by the field existing between the plates of the condenser. This slight shift of charges is the basis of the induced polarization of the dielectric (Ref. 1). This action is not limited to condensers, but exists wherever there are bodies in an electric field, both macroscopic bodies and atomic particles. A polarized particle, because of the shift of charge, has an electrical moment equal to the product of the charge times the distance between charges. In addition to these induced dipoles, many molecules have permanent dipoles that are independent of an external field. Typical molecules having permanent dipoles are water and oxygen.

The significant feature of the electrical dipole, either induced or permanent, is that it affords a means of applying a controlled force directly to the individual neutral molecule. Two effects are possible. The polarized molecule can be oriented in the direction of the local field. In a nonuniform field, a direct force on the molecule exists to move the molecule in the field. The molecules will be oriented in both uniform and nonuniform fields, but a force will act on the polarized molecules only in a nonuniform field. It should be remembered that with macroscopic bodies of high conductivity, no large internal fields can exist and no internal charge separations can take place. External charge-induction effects can take place, however.

The last electrostatic influence to be considered is that of the mechanical stress induced in a dielectric due to the applied field. Under the influence of the field, a tension known as electrostriction is produced within the material. This tension is analogous to the phenomenon of magnetrostriction and is related to the piezoelectric effect in crystals. The internal stress is the internal reaction to the forces exerted on the dielectric by the charged plates (i.e., the field between the plates).

Magnetic Influences

Let us next consider the effects of magnetism. Magnetic influences include paramagnetism, diamagnetism, and ferromagnetism. A bar of material which aligns itself parallel to an externally applied magnetic field is an example of paramagnetism. Paramagnetism occurs when the electron orbits, which act as small magnetic dipoles, become oriented with the applied field. Ferromagnetism is similar to paramagnetism but the effect is much, much larger. Ferromagnetism is best illustrated by the familiar iron magnet. A diamagnetic body tends to align itself perpendicular to the applied field because of the gyroscopic precession of the electron orbits within the molecules of the substance.

Both paramagnetic and diamagnetic influences are weak when compared to ferromagnetism, and diamagnetic effects are only approximately one-tenth to one-hundredth those of paramagnetism. Diamagnetism can be observed only in substances which have no paramagnetism, since even a small paramagnetic influence will mask out the diamagnetic effect. Certain inert gases such as N_2 exhibit diamagnetism, whereas O_2 exhibits paramagnetism (Ref. 1). Under the influence of a divergent magnetic field, paramagnetic substances are attracted toward the converging field lines while a diamagnetic substance would be repelled. Thus, small body forces are available within the fluids, even in non-ferromagnetic materials.

Another influence which can act upon a fluid is that of magnetic stress. A substance placed into an applied field will experience an internal stress which is proportional to the square of the field strength.

The last magnetic influence to be discussed is that of the $\bar{J} \times \bar{B}$ Lorentz interaction which occurs when an electrical current flows in a magnetic field. This force is large and is the driving action behind electric motors. Since the current can be a stream of charged particles in a fluid, a large body force can be produced in a fluid if suitable electrical and magnetic fields are superimposed. As mentioned previously, this interaction forms the basis for magnetohydrodynamics (Refs. 2, 3, and 4).

In summary, several basic field and material interactions are possbile. There are the very strong Coulomb electrostatic repulsion, magnetic repulsion (ferromagnetic or induced fields), and the $\bar{J} \times \bar{B}$ Lorentz force. More subtle influences are those due to electrical dipole action and the diamagnetic and paramagnetic action. Although these effects are relatively small, they can provide a useful body force within the fluid. This discussion, however, will deal almost exclusively with the effects of applied electric fields acting alone.

OBSERVED INTERACTIONS OF ELECTRIC FIELDS

The previous discussion indicated that an applied electrical field could act on substances placed within its sphere of action. If this is so, then one should expect to find numerous examples where some influence has been observed (Refs. 5 and 6). The first observation of electric-fluid interaction was the motion of a candle flame between the charged plates of a condenser. When a high potential was applied, the flame displaced laterally and assumed a somewhat fan-shaped appearance, as shown in Figure 2. The high temperatures in a flame provide a copious supply of ions. These ions tend to drift laterally in the applied field and distort the shape of the flame.

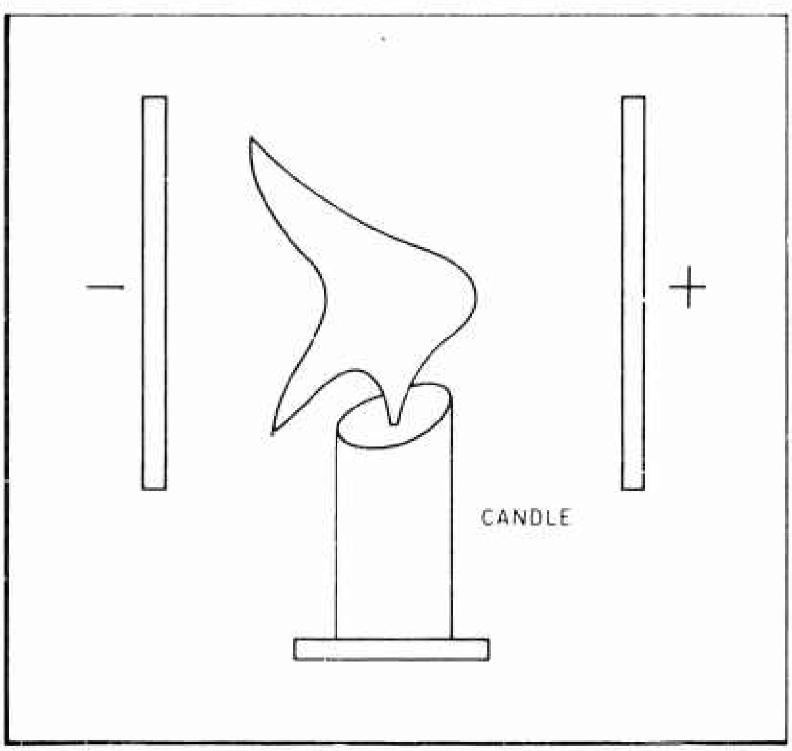


Figure 2. Distortion of a flame by an electric field

Electrolytic action in liquids was first observed long ago, and played a key role in the early development of chemistry. Electrolytic action in a solution is due to the drift of the ions to the anode and cathode. More recently, gaseous conductors have played an important role in the development of electronics. Various gas tubes, discharge tubes, arcs, and similar uses of conducting gases have been studied extensively. All of these involve moving charges -- ions, electrons, or mixtures -- under the action of the field.

Let us consider next a large group of lesser known effects. Dust particles that carry a charge may be removed by an applied field. If a natural charge does not exist on the particles, suitable charges can be induced. This action forms the basis for the various electrostatic precipitators used in home and industry. The air close to a waterfall is charged (Ref. 7); the fine mist carried aloft is generally negatively charged and the spray nearer the waterfall has a positive charge. The charges are thought to be induced by the shattering of the water upon impact and the bubbling at the water surface. Similar electrification phenomena include charged sprays over ocean waves, spray out of nozzles, and steam exhausted through a nozzle (Refs. 8 and 9). Further discussion on the mechanism of charging in these cases will be taken up later.

Electric wind, because of its recent application to lifting devices, has received a great deal of attention. Electric wind is a current of air flowing from a highly charged point electrode in air (Refs. 5 and 6). It can be demonstrated by applying a high voltage between a needle point and a plane surface, as shown in Figure 3. The air stream so generated will blow out a candle flame. A corollary effect is that of electric wind (ion drag) pressure generation (Ref. 10). In this case, several highly charged points are placed in series, and the resultant electric wind builds up a pressure. Large numbers of ions are created at the point due to the intense local fields, and these ions drift in the electric field. Momentum is transferred between the ions and the neutral molecules, resulting in a streaming of the gas as a whole. The effect is considerably greater in liquids than in gases.

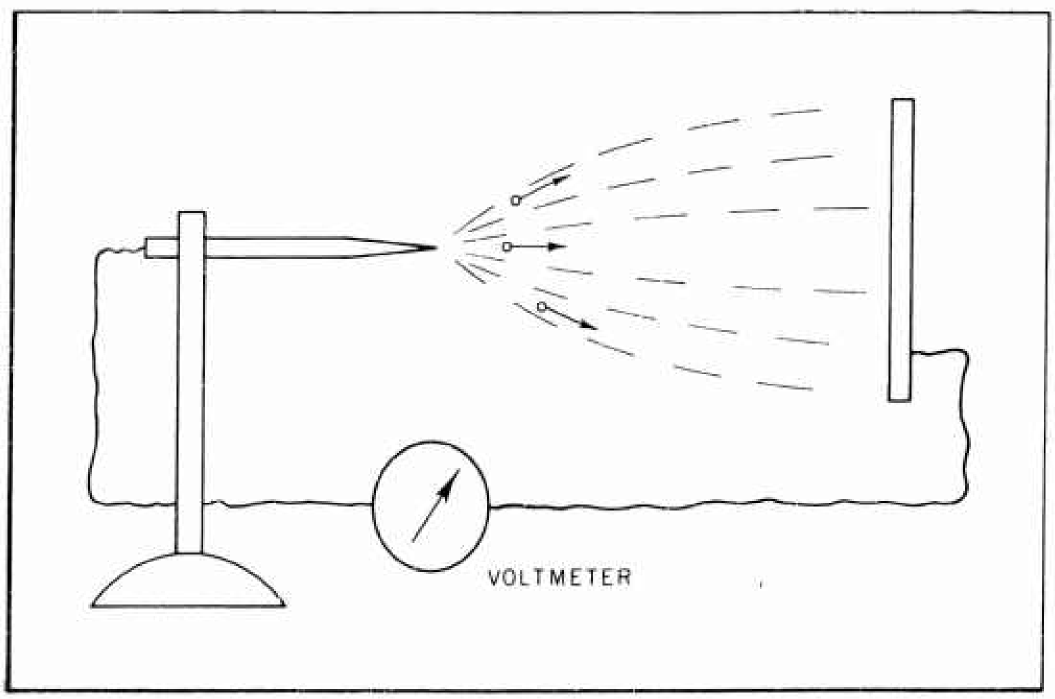


Figure 3. Electric wind induced by a charged point

The next group of effects are considered together. These effects all involve the movement of charged particles in a field, but not necessarily ions. Only a listing of the effects will be given at this point; details will be discussed later. The phenomena are: streaming potential or flow electrification, electrophoresis, dielectrophoresis, electro-endosmosis, and Dorn effect (Refs. 11, 12, and 13). Streaming potential is observed as the build-up of extremely high voltages when fuels are pumped through lines. Many cases indicate a high static charge was generated in the fueling of aircraft that has caused large sparks and fires. This phenomena has been the subject of considerable study to determine the causes and means of control. Electrophoresis is presently utilized extensively in biochemistry as a means for separating and identifying various substances, such as proteins, for example. Electrophoresis has also been used for plating or coating, since this technique provides a relatively high rate of build-up. Fluids have been pumped by using the electrophoretic effect. Dielectrophoresis is the drift of uncharged particles in a nonuniform electric field. It has been used to separate various materials suspended in solution and to pump or to change the orientation of dielectric fluids. This effect has a very significant influence on free-convection heat transfer in liquids. Electro-endosmosis has been observed in liquids as the ability of a field to elevate a portion of a fluid in a container. If a container is divided into two segments connected by a porous plug, applying a voltage across the fluids will change the elevation of the fluids in the two segments. The Dorn effect is similar to the foregoing. The Dorn effect is the difference in potential that is built up in a liquid as a suspensoid slowly settles downward in a container under the influence of gravity.

Another phenomenon is the Kerr cell. The Kerr cell acts as an electrical light shutter. An electric field applied to certain liquids will change the ability of the liquid to transmit light. By applying a rapidly oscillating potential to the liquid, a beam of light can be cut up into segments. This phenomenon is dependent upon the inter-relationship between the refractive index and the dielectric constant of a given material. This relationship was first deduced by Maxwell from his field equations (Refs. 1 and 14).

Electrostriction produces a change in the volume of a substance. Because of this, thermodynamic properties can possibly change. All thermodynamic quantities that depend upon volume can be influenced, and the influences would be a function of the square of the local field strength.

Electric propulsion uses electric field effects extensively. The thermal arc thrustor uses an extremely high current arc to heat the hydrogen propellant to very high temperatures and a nozzle to expand the gases and produce useful thrust. The ion engine accelerates the ions of the propellant (cesium, for example) to very high velocities. The cesium ions are ejected by the field to produce useful thrust at specific impulse values of 5000 to 20,000 seconds.

Power may be generated by the inverse electric wind effect (Refs. 15, 16, and 17). Analyses and preliminary tests have shown that the deceleration of charged particles (ions or droplets, for example) can be used for producing useful power. This action formed the basis of the Armstrong electrostatic generator, which was used late in the 19th Century.

The last effects to be mentioned in this section are not directly related to fluids. They may be of general interest, however, and do illustrate the influence of fields on materials. Field emission is used either to extract electrons from the surface of a metal or, with sufficient strength, to extract the ions from the crystal lattice. This action forms the basis for the electron-field and the ion-field microscopes. Field emission has also been used to provide a source of electrons for various electronic devices. Exploding wires demonstrate a combination of electrical effects when enormous currents are discharged through small wires during a very short time interval. Static charging phenomena are probably the oldest form of electrification known. However, the basic mechanisms of charge separation in solid-solid contact is complex and apparently not clearly understood. Actions of contact potential, Volta potential, adsorbed layers of water, and physical transfer of electrons and ions under high local fields are all involved in various forms of static electrification. Tribo electrification or frictional electrification is of this type and occurs as solid-solid contact phenomena in dry surfaces (Ref. 7). While solid-solid electrification is not of primary concern here, the mechanism of charge generation by air flowing over a surface and combustion gas flowing out of a nozzle, for example, will directly influence the state of charge in flowing fluids.

Thus, many effects of electric fields on fluids have been observed. Some have been studied extensively, and others little or not at all. The wide range of effects, however, encourages study of electric-fluid interaction.

OBSERVED EFFECTS OF ELECTROMAGNETIC FIELDS

The actions of electromagnetic fields on fluids has led to the development of electromagnetic pumps and many magnetohydrodynamic applications. Many, many effects have been shown to take place, including apparent changes of fluid properties, velocity profiles, boundary layers, and heat transfer. These effects are thoroughly covered in the literature on magnetohydrodynamics. In this study of electric field effects, therefore, magnetic field effects will not be discussed further.

ACTION OF ELECTRIC FIELDS ON PARTICLES

ACTION ON CHARGED PARTICLES

To provide a firm basis for a more detailed discussion of the observed electric field effects, a review of the action of fields on particles will be covered next. Fundamental to this discussion are the basic equations of electricity and magnetism. Maxwell's relations for electromagnetism summarize the basic phenomena of electricity (Ref. 3). These relations are:

$$\left.\begin{aligned}
\bar{\nabla} \times \bar{H} &= \bar{J} + \frac{\partial \bar{D}}{\partial t} \\
\bar{\nabla} \times \bar{E} &= -\frac{\partial \bar{B}}{\partial t} \\
\bar{\nabla} \cdot \bar{E} &= \rho \\
\bar{\nabla} \cdot \bar{B} &= 0 \\
\bar{J} &= \sigma (\bar{E} + \bar{v} \times \bar{B}) + q\bar{v} \\
\bar{F} &= q\bar{E} + \bar{J} \times \bar{B} \\
\bar{D} &= \epsilon \bar{E} = \epsilon_0 \bar{E} + \bar{P} \\
\bar{B} &= \mu \bar{H}
\end{aligned}\right\} \quad (2)$$

where:

$\bar{J}$ = current density,

ρ = charge density,

$\bar{D}$ = electric flux density,

$\bar{E}$ = electric field strength,

ϵ = dielectric constant,

$\bar{P}$ = polarizability,

ϵ_0 = dielectric constant (vacuum),

q = charge,

$\bar{v}$ = velocity of charge,

$\bar{B}$ = magnetic flux density,

$\bar{H}$ = magnetic field,

μ = magnetic permeability, and

σ = electric conductivity.

For the cases involving no externally applied magnetic field, the number of applicable equations is reduced and simplified. To illustrate the use of the equations, consider the motion of a single ion in a uniform field formed by two flat plates. The applicable equations are:

$$\bar{\nabla} \cdot \bar{D} = \rho$$

$$\bar{D} = \epsilon \bar{E}$$

$$\bar{E} = -\nabla V$$

where:

V = potential.

If E is a constant, then

$$\nabla = \frac{\partial}{\partial x}$$

$$E_x = \text{constant} = -\frac{\partial V}{\partial x}$$

$$V = -E_x\, x + C_1$$

$$C_1 = 0 \;; \quad V = 0 \quad \text{at} \quad x = 0$$

Therefore,

$$V = -E_x\, x. \tag{3}$$

Consequently, voltage is a linear function of distance.

Under the influence of the field, $\bar{F} = q\bar{E}$,

$$m\ddot{x} = q E_x$$

$$\dot{x} = \frac{q}{m} E_x t + C_1 ,$$

where:

m = the mass of the particle.

If at $t = 0$, $\dot{x} = 0$, then $C_1 = 0$, and:

$$x = \frac{q}{2m} E_x t^2 + C_2 .$$

If at $t = 0$, $x = 0$, then $C_2 = 0$, and:

$$x = \frac{q}{2m} E_x t^2 \tag{4}$$

This result, which is similar to the motion of a body falling in a uniform gravitational field, represents the motion of a charged particle in a uniform field. It could also represent the motion of an ion between collisions when moving in a neutral gas.

Motion of a charge in the field of another point charge will occur along a radial line. Because of spherical symmetry, Poisson's equation will reduce in complexity. Poisson's equation can be written as:

$$\bar{\nabla} \cdot \bar{D} = \rho$$

or

$$\nabla^2 V = -\frac{\rho}{\epsilon} .$$

If the moving charge is small and is assumed to have negligible influence on the applied field, then

$$\nabla^2 V = 0$$

In spherical coordinates:

$$\nabla^2 V = \frac{1}{r^2} \frac{\partial}{\partial r}\left(r^2 \frac{\partial V}{\partial r}\right) + \frac{1}{r^2 \sin\theta} \frac{\partial}{\partial\theta}\left(\sin\theta \frac{\partial V}{\partial\theta}\right) + \frac{1}{r^2 \sin^2\theta} \frac{\partial^2 .}{\partial\phi^2} .$$

Symmetry reduces this equation to:

$$\frac{1}{r^2} \frac{\partial}{\partial r}\left(r^2 \frac{\partial V}{\partial r}\right) = 0 ,$$

and then:

$$r^2 \frac{\partial V}{\partial r} = C_1 ,$$

$$dV = \frac{C_1}{r^2} dr$$

$$V = -\frac{C_1}{r} + C_2 .$$

If $V = 0$ at $r \to \infty$, then $C_2 = 0$.

Therefore:

$$V = -\frac{C_1}{r} \tag{5}$$

and

$$E = -\frac{\partial V}{\partial r} = \frac{C_1}{r^2} .$$

Using this, the equation of motion is:

$$\frac{d^2 r}{d t^2} = \frac{q}{m} C_1 \cdot \frac{1}{r^2} .$$

Let v = dr/dt and dr = vdt. Then:

$$v\,dv = \left(\frac{qC_1}{m}\right) \frac{dr}{r^2}$$

$$\frac{v^2}{2} = -\frac{qC_1}{m} \int_{r_0}^{r_1} \frac{dr}{r^2} + C_2 .$$

If $v = v_0$ at $r = r_0$, then:

$$(v^2 - v_0^2) = \frac{2q\,C_1}{m} \left(\frac{1}{r_0} - \frac{1}{r}\right) . \tag{6}$$

This is the equation for the velocity of motion of a charged particle in a spherically shaped electrical field.

The motion of a moving charged particle in a magnetic field will be of interest later, so we will derive the equation for this motion at this point. The force on a moving charge or on a current in a magnetic field is analogous to the forces and torques on the windings of an electric motor. It can be represented by:

$$\bar{F} = \bar{J} \times \bar{B}$$

where:

$$\bar{J} = q\bar{v} .$$

Therefore:

$$\bar{F} = q\bar{v} \times \bar{B} .$$

If the charged particle enters a magnetic field moving with a velocity, v, in a plane normal to the magnetic flux, then the equation reduces to a scalar equation:

$$F = qvB . \tag{7}$$

The direction of this force is normal to both the magnetic field and the velocity of motion. Such a force causes the direction of motion to change but not the magnitude of the velocity. Consequently, the force is constant in magnitude and the direction is always perpendicular to the velocity. Such a force causes the particle to move in a circle. The acceleration of the particle and the radius of the circle can be readily determined by:

$$F = ma = qvB$$

$$a = \frac{qvB}{m} = \text{acceleration.}$$

In a circular path:

$$a = \frac{v^2}{r}$$

Equating these two expressions:

$$\frac{q v B}{m} = \frac{v^2}{r}$$

$$r = \frac{mv}{qB} \quad . \tag{8}$$

A charged particle moving without an external electric field will begin to rotate about the magnetic lines of force when entering a magnetic field. If, in addition, the particle has a velocity in the direction of the field, it will spiral along the flux line at a constant radius. This elementary introduction to the action of the moving charge in a magnetic field, we believe, will be sufficient for the subsequent discussion.

As a charged particle moves in a dense fluid under the influence of an electric field, its motion is retarded by an effective drag exerted by the fluid. This effect on the motion of an ion moving through a gas is included in the concept of ion mobility (Refs. 18 and 19). As the ion moves in a field, it accelerates quickly to a characteristic velocity along the field, called the ion drift velocity. In dense gases, this velocity is approximately proportional to the applied field strength, providing the field strengths are not so high as to cause breakdown (a spark for example).

The drift velocity, then, is given by:

$$v = KE \tag{9}$$

where: K = the ion mobility.

This motion, as can be noted from the following equations, differs from the motion of a single ion in free space where the field is uniform:

Single ion: $v = \frac{(qE)}{m} t$

Ion in a gas: $v = KE$.

Based upon the elementary kinetic theory of gases:

$$K = \frac{eL}{m\bar{c}} \tag{10}$$

where:

e - charge on the ion,

L = mean free path of gas,

$\bar{c}$ = mean speed of molecules, and

m = mass of the ion.

This expression is based upon the assumption that the ion accelerates between impacts with neutral molecules after having been stopped at each collision. Derivations by Compton, Langmuir, and others have led to more refined expressions for mobility. The simple equation (Eq. 10), however, illustrates the general dependence of mobility on the basic characteristics of the gas and ion, namely, that mobility depends upon the mean free path, mass, and mean free speed of the molecules, as well as the magnitude of the charge on the ion. It has been observed during tests that the mobilities of negative and positive ions of the same molecules are different. Negative ions usually move more rapidly through a given field than positive ions. Because of this phenomenon, the distribution of ions in a uniform field will generally not be symmetric.

To illustrate the possible distribution of charged particles under the influence of a uniform field, two examples will be given. First, the distribution will be established assuming none of the charges are neutralized at the wall, i.e., no current flows.

If no mass motion of the fluid occurs and a stationary state is reached, then the pressure rise due to ion distribution in the field will be given by:

$$\frac{dp}{dx} = -F_x$$

where: F_x = the force acting on the ion gas due to the electric field.

$$F_x = \rho E_x$$

$$\rho = n_i q_i$$

$$F_x = n_i q_i E_x$$

where:

E_x = field in x direction,

n_i = number of ions/unit volume, and

q_i = charge per ion.

From kinetic theory:

$$p = \frac{1}{3} \frac{\gamma}{g} \bar{c}^2 = \frac{\gamma RT}{gm}$$

where:

T = assumed constant, and

$\frac{\gamma}{g}$ = ion gas density = $n_i m$.

Substitute this into the equation for pressure rise:

$$RT \frac{dn_i}{dx} = -q_i E_x n_i \quad .$$

Therefore:

$$n_i = A e^{-\frac{q_i E_x x}{RT}} \tag{11}$$

Thus, the ion density distribution in this simple illustration is of the same exponential form as the variation in density of the air in an isothermal atmosphere.

Next, let us consider gaseous conduction between two parallel plates with an applied potential. As the voltage is raised, the charges migrate to the plates. Negative ions move toward the positive plate, and positive ions move more slowly toward the negative plate. As the voltage is increased, a large number of charged particles move close to the plate and effectively cancel the applied field in the vicinity of the electrode. This condition exists in front of both plates and results in a distribution of potential between the plates; a sharp drop in potential occurs near each electrode and a very small drop in the center as shown in Figure 4.

The congregation of charge near the plates is known as space charge. Space charge can also occur in the vicinity of a heated cathode emitter. As large numbers of electrons are emitted, the electrons in the vicinity of the cathode shield the cathode and create a space charge directly in front of the cathode. The amount of current that can flow is then limited.

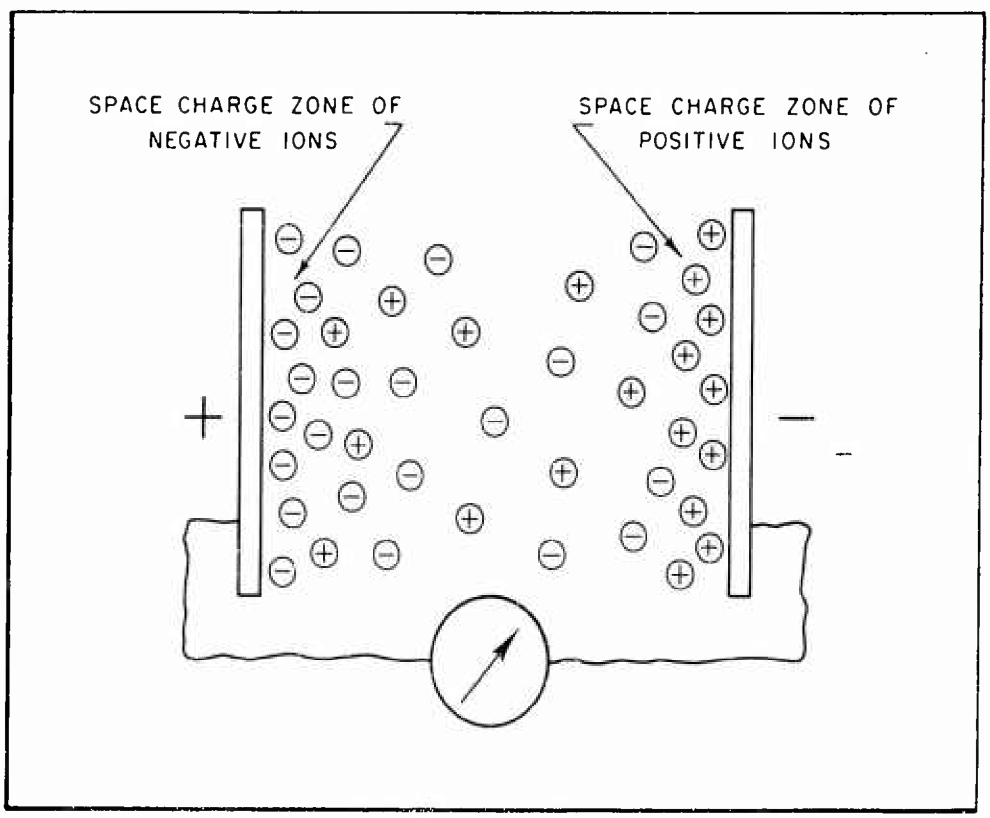


Figure 4. Illustration of space charge

In a high density gas, the potential distribution for electrons (Ref. 19) is:

$$V = \frac{2}{3}\left(\frac{8\pi J}{K}\right) x^{\frac{3}{2}} , \tag{12}$$

and the current density is:

$$J = \frac{q}{4} \; \frac{K V^2}{8\pi x^3} . \tag{13}$$

In a high vacuum, the current distribution for electrons is given by Child's law:

$$J = \frac{\left(2\,\frac{e}{m}\right)^{\frac{1}{2}} V^{\frac{3}{2}}}{q\,\pi\, x^2} . \tag{14}$$

It can be seen that the current distributions, and thus the charge distributions, can vary widely, even in the simple case of a uniform field between flat plate electrodes.

Knowledge of the distribution of ions is important because the forces exerted within a fluid can depend directly on the number of ions that exist in the fluid. In the previous discussion of ion motion in fields, the only factors taken into account were the electric field and the ion density. Effects of charge generation, recombination, and diffusion have not been considered. These influences can be large in specific cases, but the solution of the complete equations is complex. The complete equations for the simple one-dimensional case with both positive and negative ions (Ref. 19):

$$\left.\begin{aligned} & q - \alpha_i\, n_1 n_2 + D_1 \frac{d^2 n_1}{dx^2} - K_1 \frac{d}{dx}(E n_1) = 0 \\ & q - \alpha_i\, n_1 n_2 + D_2 \frac{d^2 n_2}{dx^2} + K_2 \frac{d}{dx}(E n_2) = 0 \\ & \frac{dE}{dx} = -(n_1 - n_2)\, e \end{aligned}\right\} \tag{15}$$

where:

α_i = coefficient of recombination,

n_1 = number of positive ions,

n_2 = number of negative ions,

q = rate of charge generation,

D_i = coefficient of diffusion,

K_1 = mobility of positive ions, and

K_2 = mobility of negative ions.

Directed motion of a charge normally takes place under the action of a steady-state electric field. If a time-varying, AC, field is applied, we might expect the charge to merely oscillate back and forth in the field. A charge in a uniform time-varying field will oscillate so. A charged particle in a nonuniform time-varying field, however, will act differently, depending on the phase between the velocity and the field. For illustration, consider a charge moving under the influence of a divergent field. If the charge moving under the influence of a divergent field. If the charge moves outward when repelled, it covers a definite distance from the center of the field. At this point in space, the magnitude of the field is decreased, but the particle has acquired a definite velocity. As the sign of the field is reversed, the particle is accelerated back toward the center of the field, but the accelerating force is smaller than the previous repulsion force. With a purely sinusoidal variation of field, the particle cannot regain its original position. As a consequence, the particle may acquire a mean motion away from the center of the field, as shown in Figure 5. The ion, therefore, acquires a net drift as the result of the non-steady applied AC field (Ref. 20).

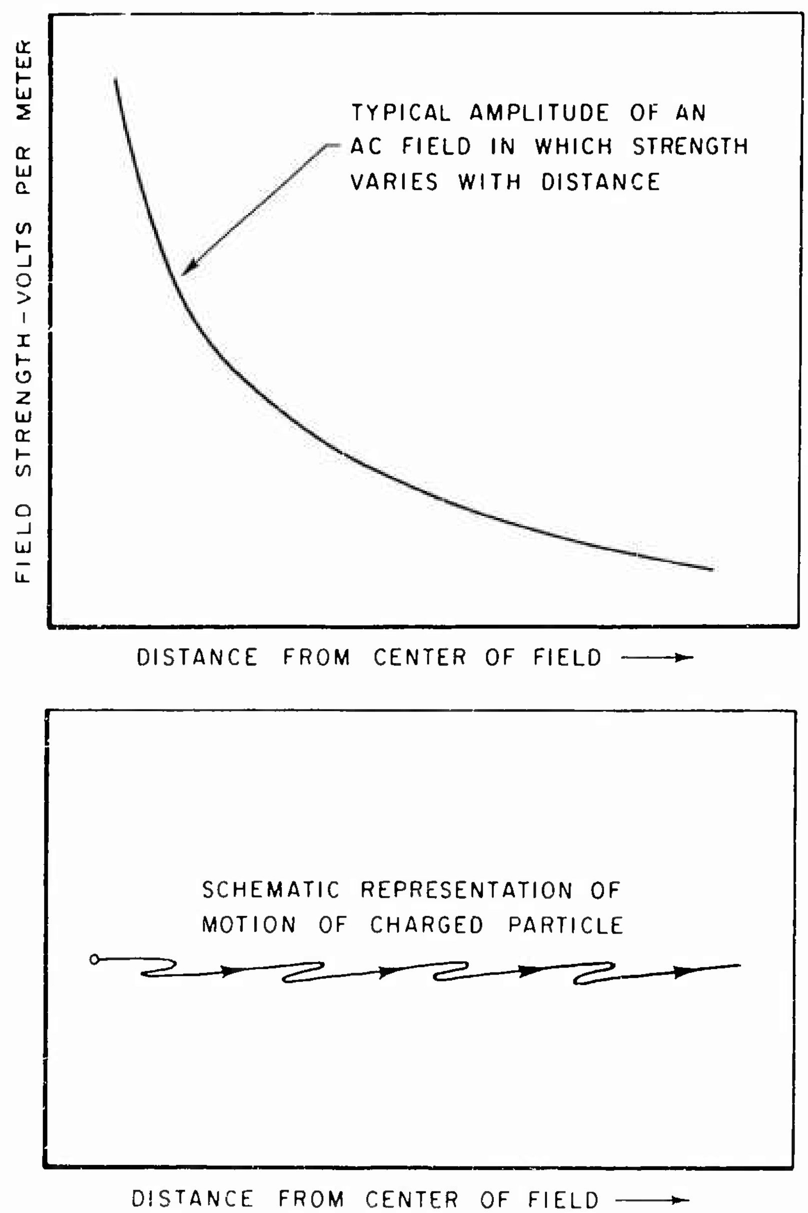


Figure 5. Motion of a charged particle in an AC field

The equation of motion of a particle in a spherical field of the Coulomb type would be:

$$m\ddot{r} = \frac{q_1 q_2}{4\pi\epsilon r^2} \sin \omega t \tag{16}$$

where:

m = mass of particle,

q_1 = charge of particle,

q_2 = charge at center of field,

ϵ = dielectric constant, and

ω = frequency of field variation.

Letting

$$a = \frac{q_1 q_2}{4\pi\epsilon m}$$

the equation can be written as:

$$\ddot{r} = \frac{a}{r^2} \sin \omega t \tag{17}$$

Since this equation is nonlinear, an elementary solution does not appear possible. It is somewhat similar to Hill's equation and Mathieu's equation which arise in the analysis of the forced oscillation of an inverted pendulum. This equation would have to be solved by perturbation or iterative methods. Attempts to study the stability by Poincare's method were not successful due to the form of the $\frac{\sin \omega t}{r^2}$ term.

If a linear-force field gradient is assumed possible, then the equation of motion becomes:

$$\ddot{r} = ar \sin \omega t \tag{18}$$

This is also a Mathieu equation, and no elementary solution is possible.

Care must be used in interpreting any motion effect. The scope of this research study does not permit studying the behavior of such equations extensively. In any specific case, a step-by-step iterative solution can be utilized.

In summary, this section has outlined the factors that affect the motion of a charged particle in an externally applied field. The illustrations indicate how a particle drifts in the field and possible distributions of charge.

DIELECTRIC ACTION ON NEUTRAL PARTICLES

The next topic to be considered in electrofluid interactions is dielectric effects. The most common use of dielectric effects is in capacitors. When an ideal dielectric is placed between charged plates, the electrons are tightly bound and cannot move freely through the material to the plates. Since the charges cannot move freely to neutralize the applied field, an internal field will exist within the dielectric (Ref. 1).

Considering Coulomb's law:

$$\bar{F} = \frac{q_1 \, q_2}{4 \pi \epsilon r^2} \, \bar{a}$$

it can be seen that as the value of the permittivity (dielectric constant) is increased, the force between the charges is reduced. Likewise, the electric field between the charges is reduced. The action of the dielectric stems from the formation and orientation of molecular electric dipoles within the dielectric. When an atom is placed in an electric field, the positively charged nucleus and the electron cloud separate slightly, as shown in Figure 6. This displacement of charge creates an electrical dipole moment: the positive nucleus tends to move toward the negatively charged plates and the electron cloud shifts toward the positively charged plates. This field-induced dipole will form with all atoms and molecules in varying degrees, and in uniform and nonuniform electric fields.

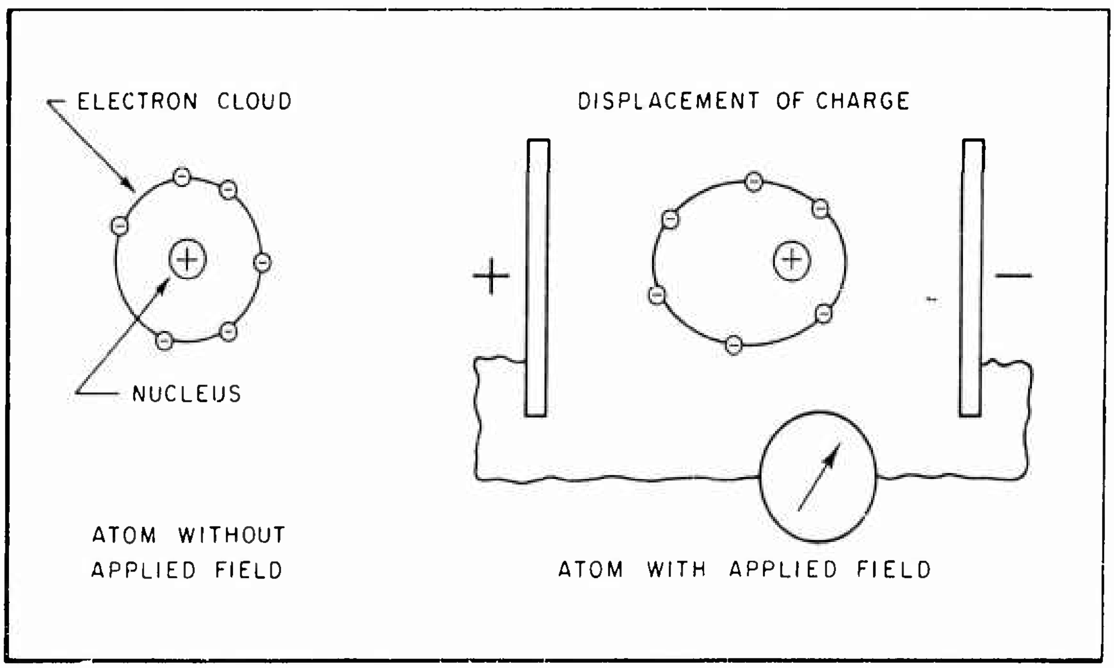


Figure 6. Formation of induced dipole-displacement of charge

Many molecules have dipoles as an inherent part of their structure due to the arrangement of the atoms in the molecule. A typical molecule with a dipole is water. The total dipole moment of any molecule is the sum of its permanent and field-induced dipoles. The formulation for the electrical dipole is illustrated by the expression of Debye (Refs. 1 and 21):

$$\eta = \eta_0 + \frac{\mu^2}{3kT} \tag{19}$$

where:

η = polarizability of a single molecule,

μ = permanent dipole of the molecule,

k = Boltzmann's constant,

T = absolute temperature, and

η_0 = constant not influenced by temperature.

Since the dipole moment is given by:

$$p = \eta E$$

where:

p = molecular dipole moment and

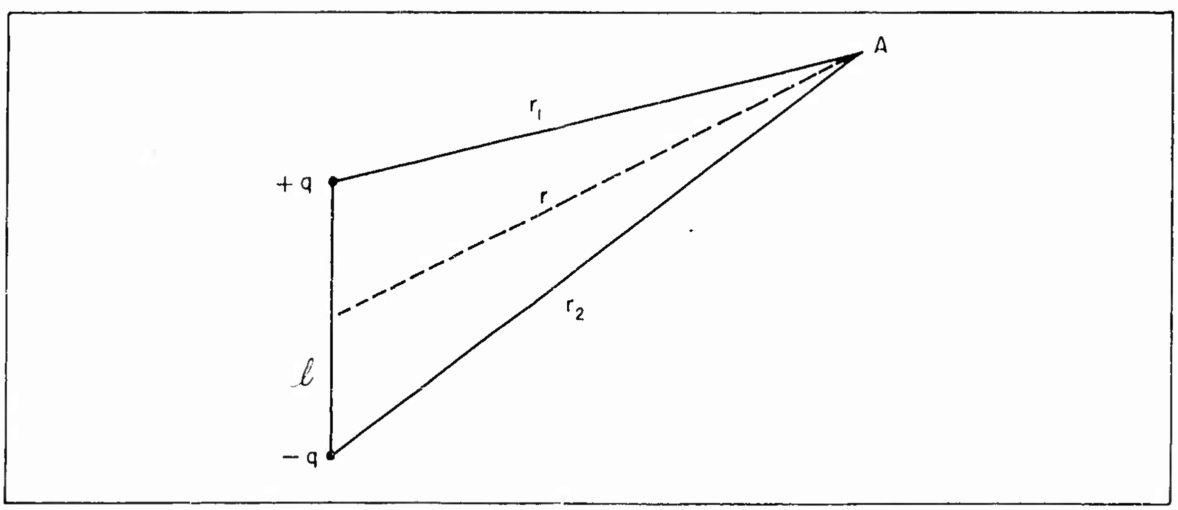
E = field strength,

then:

$$p = E\left(\eta_0 + \frac{\mu^2}{3kT}\right). \tag{20}$$

An electric field applied to a dipole will cause the dipole to orient itself in the direction of the field. If the molecules of the dielectric have a large permanent dipole, the orientation effects can be strong. In studies of electro-fluid mechanics, any interactions with neutral molecules can be expected to be most pronounced in those fluids containing molecules of large dipole moments. Such, indeed, is the case, as will be illustrated later in discussions of electroviscosity and heat transfer. The mechanisms of interaction between the dipoles, ions, and the applied field, however, are of fundamental importance and, consequently, dipoles will be considered here in more detail (Ref. 3).

Let us examine the nature of the electrical dipole, as shown in the following sketch:



The dipole moment, given by $p = q\ell$, is the product of the charge strength and the distance separating the two equal but opposite charges. If the distance between the charges were zero, the net charge would be zero and the resultant field would be zero. As the charges are separated, however, the dipole is formed. The system of the two charges is electrically neutral, but there is a net resultant field from the dipole.

The potential at A due to +q is:

$$V_1 = \frac{+q}{4\pi\epsilon r_1}$$

and due to -q is:

$$V_2 = \frac{-q}{(4\pi\epsilon r_2)} .$$

Since $\bar{r}_1 \neq \bar{r}_2$, the net potential at A for relatively large distances is

$$V = \frac{q\ell\cos\theta}{4\pi\epsilon r^2} = \frac{p\cos\theta}{4\pi\epsilon r^2} . \tag{21}$$

Using the relation $E = \nabla v$ to find the field strength, we find:

$$E = -\bar{a}_r \frac{\partial v}{\partial r} - \bar{a}_\theta \frac{1}{r} \frac{\partial v}{\partial \theta}$$

$$= \bar{a}_r \frac{q\ell\cos\theta}{2\pi\epsilon r^3} + \bar{a}_\theta \frac{q\ell\sin\theta}{4\pi\epsilon r^3} \tag{22}$$

where:

$\bar{a}_r$ = a unit vector in r direction, and

$\bar{a}_\theta$ = a unit vector in θ direction.

The most important points to be noted from these equations are that a resultant field exists and that it varies inversely as the cube of the distance from the dipole.

Polarization of a dielectric is defined as the dipole moment per unit volume:

$$P = \frac{q\ell}{v} = \text{polarization per unit volume.}$$

The flux density in a dielectric is related to the polarization by the equation:

$$D = \epsilon_0 E + P = \left(\epsilon_0 + \frac{P}{E}\right) E .$$

But

$$D = \epsilon E ,$$

Therefore:

$$\epsilon = \epsilon_0 + \frac{P}{E} ,$$

$$P = E(\epsilon - \epsilon_0) \tag{23}$$

Consider the action of an applied nonuniform field on a dipole located within the field. Assume that the dipole has oriented itself along the direction of the field, as shown in Figure 7.

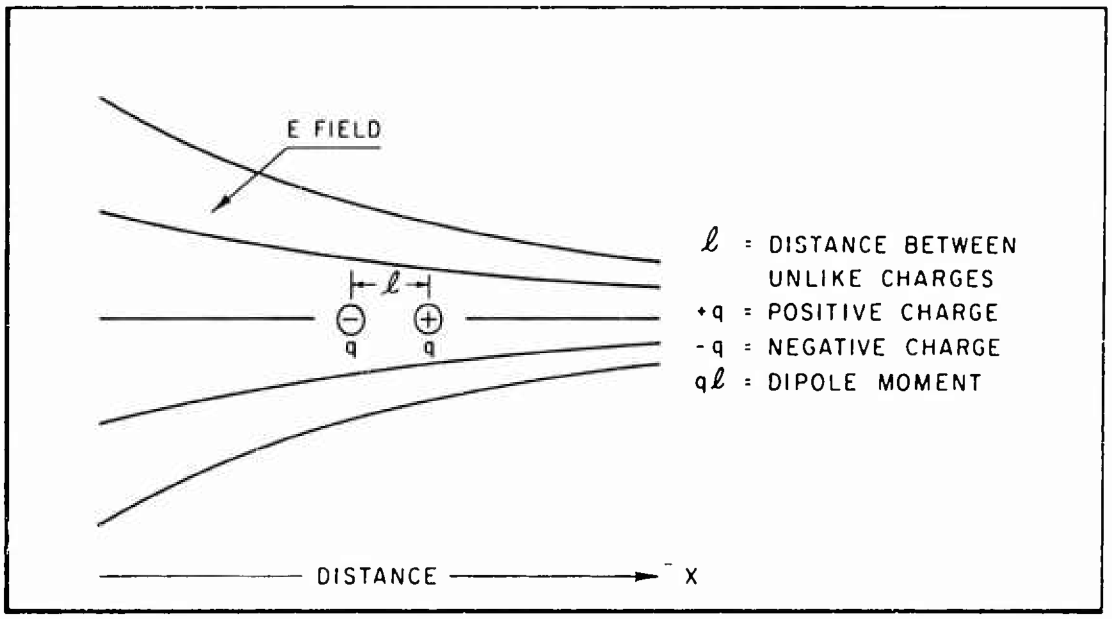


Figure 7. Action of nonuniform field on a dipole

The summation of forces in the x direction per unit volume gives:

$$\Sigma F_x = -qE + \left(qE + q \frac{\partial E}{\partial x} \delta x \right) = (q \delta x) \frac{\partial E}{\partial x} .$$

Since the distance traveled along the x direction between charges is ℓ, then $\delta x = \ell$, and:

$$\Sigma F_x = q\ell \cdot \frac{\partial E}{\partial x} .$$

The force per unit volume is:

$$F_x = q\ell \cdot \frac{\partial E}{\partial x} = P \frac{\partial E}{\partial x} .$$

Substituting for P, we obtain:

$$F_x = (\epsilon - \epsilon_0) E \frac{\partial E}{\partial x} = \frac{(\epsilon - \epsilon_0)}{2} \frac{\partial E^2}{\partial x} \tag{24}$$

This equation indicates that a body force exists within a dielectric whenever there is a gradient in the field strength. If grad $\bar{E}$ is zero, then no body force exists. The magnitude of the body force depends upon the difference in permittivity between the dielectric and vacuum and the gradient of the square of the field strength. Since the force is a function of the square of the field strength, its direction remains the same regardless of the sign of the field. An alternating nonuniform field (time varying) would thus result in a force which is always directed toward the region of highest intensity, as shown in Figure 8. As an example, consider the field around the end of a needle point. The field lines converge to this point, and the field strength increases as the point is approached. In such a case, the dielectric body force would be directed toward the point of the needle, both for DC and AC fields.

From a macroscopic view of the interactions, this dielectric body force may be the most important interaction phenomenon in fluids. There are, however, other actions.

The electric stress generated by the attraction of the charges acts as a stress on the surface of a dielectric and as an internal pressure within the dielectric. The electric surface stress results from the lines of force emanating from charges distributed over a surface. The pull on a surface having a charge density, σ, is given by:

$$F_{sur} = \int_0^{\sigma} E\,d\sigma = \frac{1}{\epsilon_0}\int_0^{\sigma} \sigma\, d\sigma = \frac{\sigma^2}{2\epsilon_0}$$

At the surface of the conductor with a surface charge density, σ:

$$D_{normal} = \sigma\ ; \quad \epsilon_0 E = \sigma\ .$$

Therefore:

$$F_{sur} = \frac{\sigma^2}{2\epsilon_0} = \frac{1}{2}\epsilon_0 E^2\ . \tag{25}$$

The pressure within the dielectric is given by:

$$p = \frac{(\epsilon - \epsilon_0)}{2} E^2\ . \tag{26}$$

This result is obtained by equating the dielectric body force to the resisting internal pressure on a unit volume of the dielectric (Ref. 22).

The final interaction to be considered in this section is that of the dipole interaction with charged particles (Ref. 23). In a fluid that contains both charged particles and molecules with dipoles, the charged particles may attract and influence the neutral dipole molecules. The charged particles (ions, for example) act as the point of a needle and thus provide an intense nonuniform electric field close to the particle. As a polar molecule enters this region, it is attracted in a manner analogous to that of the dielectric body in a nonuniform field. In the event the approaching molecule does not have a permanent dipole (nonpolar), then a dipole moment is induced by the field of the charge. Induced dipole attractions in nonpolar fluids, however, will be smaller than those in strong polar fluids. Although the significance of this dipole-charge interaction in macroscopic fluids is not clear, the interaction may lead to "clustering" effects because the neutral molecules would tend to cluster around the charged particle. If such effects occur to any appreciable extent, they could influence fluid properties (such as viscosity), and fluid behavior (velocity profiles, etc.). The various force relationships in the neutral-charged particle interactions are complex; further information is provided in References 18 and 24.

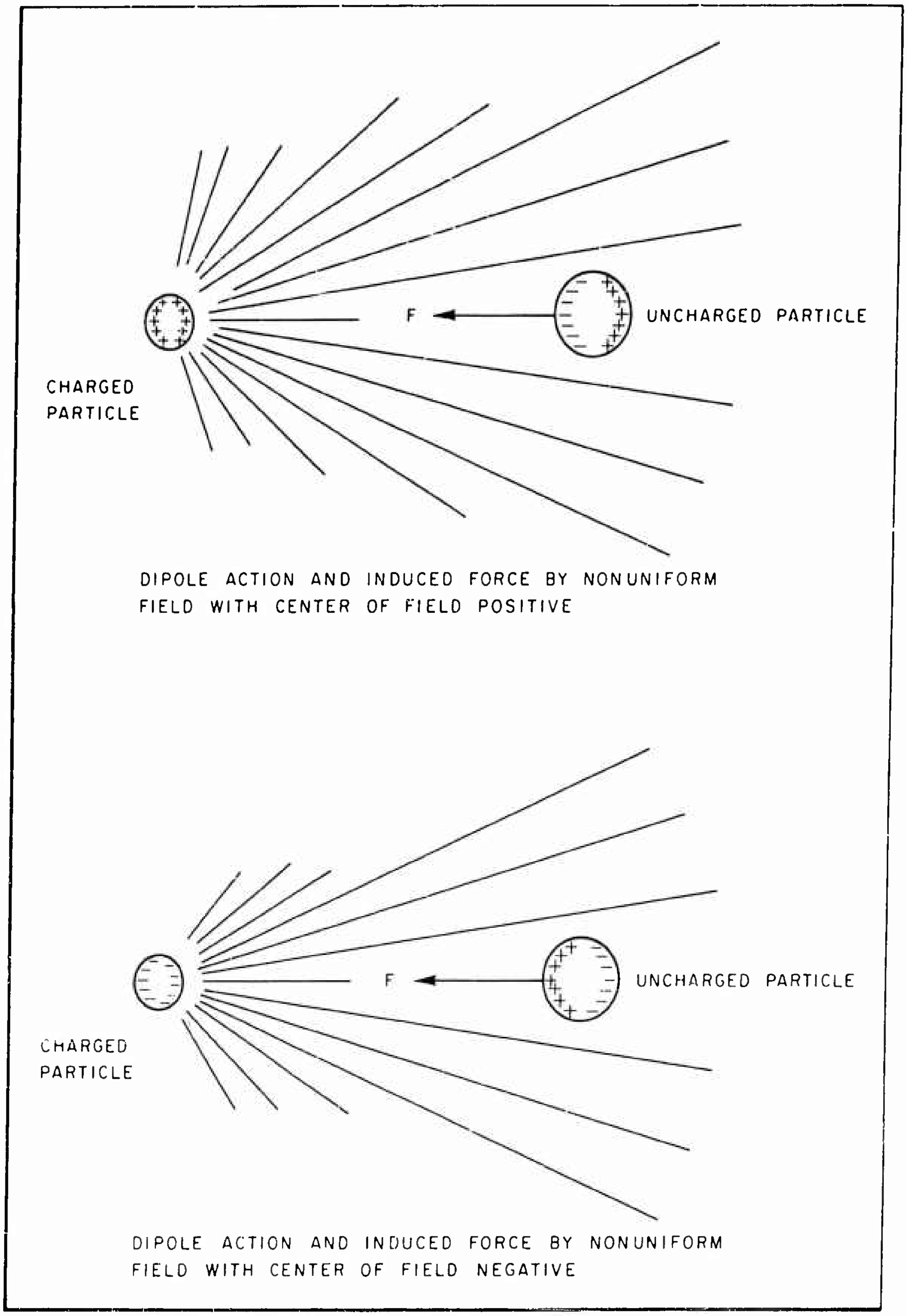


Figure 8. Force on a dipole

The nature of dielectric influences thus tends to be somewhat more complex than the more simple drift effects of the charged particle motion. These influences are of primary importance in the study of fluids, however, because we can create body forces through dielectric action within a fluid that does not contain ions.

PHORESIS

Phoresis is derived from the Greek word meaning motion. As applied to problems in physical chemistry, it relates to the drifting or motion of particles in an electric field. Several phoretic effects have been shown to take place. Ion motion during electrolysis is not generally included in phoretic effects; these effects usually pertain only to particles that are larger than atoms or molecules. These particles may include colloids, bubbles, powders, suspensions, droplets, and similar submacroscopic particles. In most cases, the phoresis effects concern motion of particles in liquids, usually nonconducting liquids. These effects are identified as follows:

1. Cataphoresis
2. Electrophoresis
3. Electro-endosmosis
4. Streaming potential
5. Dorn effect
6. Dielectrophoresis

Each one of these phenomena will be explained. Before doing so, however, we will review the concept of the Helmholtz double layer as discussed in the work of Klinkenberg and van de Minne (Ref. 12) and Loeb (Ref. 7).

At the interface between two phases (liquid and solid or bubble and liquid, for example) the charge is generally unevenly distributed. At an electrode, ions of one sign may go into solution, or ions from the liquid may be adsorbed at the surface of the electrode. In either case, a charge is built up on the surface. Assume, for illustration, that the electrode surface becomes charged positively, as shown in Figure 9. Then an accumulation of negatively charged ions builds up adjacent to the surface. These negative ions are strongly attracted by the positive surface through Coulomb attraction and form a layer of "bound" or "fixed" charge. Further into the fluid, a positively charged diffuse layer has been induced by the "bound" negative layer. The net charge of this diffuse layer diminishes until it reaches a neutral state. The combined "bound" layer and diffuse layer constitute the electrical double layer, or Helmholtz double layer.

Various experiments have shown that the diffuse layer can be moved with a mass motion of the surrounding fluid. The fluid then acquires the net charge that existed within the diffuse layer. The "bound" charge remains on the surface so that the charge is opposite to that of the moving fluid. If the fluid is a very good conductor (i.e., aqueous solutions), then the net charge difference is quickly dissipated and little potential difference is generated. If the fluid has very low conductivity, however, the charges do not neutralize readily and a large charge separation can result. High voltages can thus be generated.

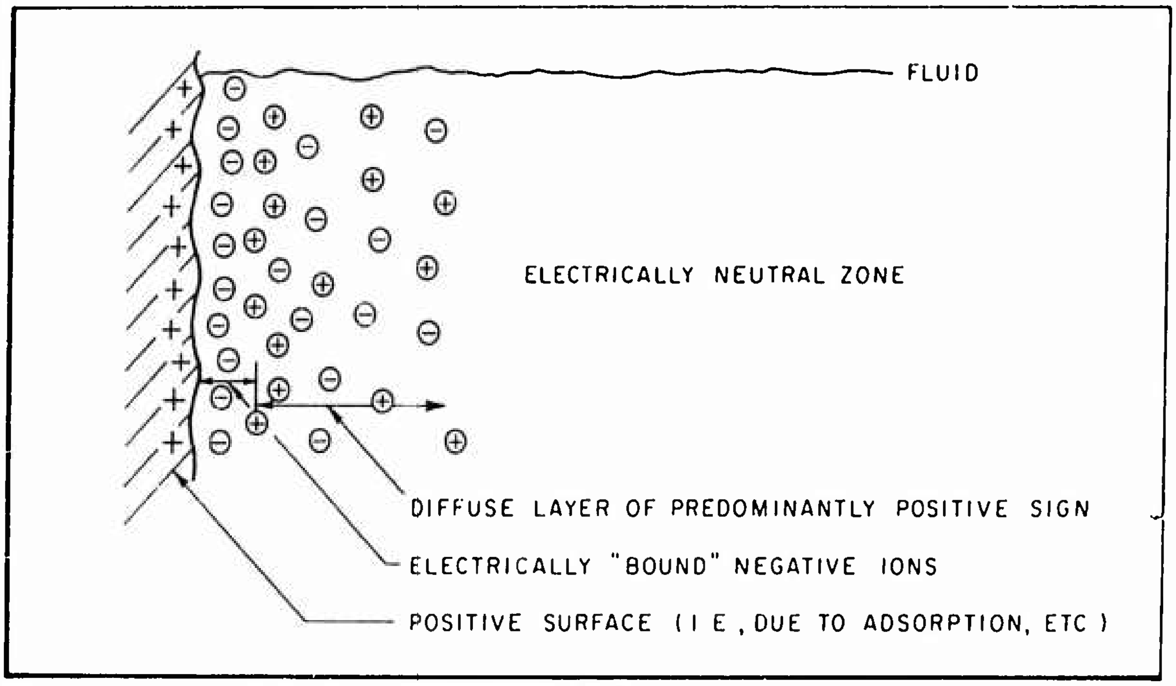


Figure 9. Helmholtz double layer

The charge per unit area, σ, of the fixed and mobile layer is given by:

$$\sigma = \epsilon \frac{V_d}{\delta} \tag{27}$$

and δ is given by:

$$\delta = \sqrt{\frac{\epsilon k T}{2 n Z e^2}} \tag{28}$$

where:

σ = charge per unit area,

V_d = potential difference across double layer,

δ = thickness of the double layer,

n = number of dissociated molecules per unit volume,

Z = valency of ions, and

e = unit charge.

Usually, the potential difference, V_d, is given as the electrokinetic potential, ζ, or the Zeta potential. It is similar to V_d but is described as:

$$\zeta = \frac{\sigma}{\frac{\epsilon}{4\pi\delta}} = \frac{4\pi\delta\sigma}{\epsilon} \qquad (29)$$

Electrophoretic mobility, analogous to ion mobility in a gas, is given by:

$$K = \frac{\zeta\epsilon}{4\pi\mu} \qquad (30)$$

where:

μ = viscosity.

With the concept of the Helmoholtz double layer in mind, we can now describe the various types of phoretic motion.

Cataphoresis

In cataphoresis, many small solid particles suspended in a liquid are involved. At the surface of each particle, an associated double layer will exist. Under the action of an imposed electric field, the outer portion (mobile layer) of the double layer will move toward one electrode and the solid particle with the bound layer will move in the other direction. Cataphoresis occurs with bubbles as well as solid particles. The forces involved are small and the effects on the large particles will be small.

Electrophoresis

Electrophoresis is essentially the same phenomenon as cataphoresis. It, however, can be construed to mean all effects of electric fields on phoresis phenomena (Ref. 25).

Electro-endosmosis

If a potential difference is deliberately set up along the axis of a narrow tube or across a plug, the liquid is pumped through the tube. If the container is a closed volume, a pressure is built up to a value sufficient to prevent further flow. The pressure generated is the electro-osmotic pressure. The action in this case is due to motion of the charged layers of the Helmholtz double layer.

Streaming Potential

Streaming potential or flow electrification is a very common phenomenon that occurs whenever a fluid flows through a tube. The fluid must have low conductivity to demonstrate the effect. As the fluid traverses the pipe, the mobile layers from the surfaces of the entrained particles are carried downstream, resulting in a large charge separation. Extremely large potential differences may result. Streaming potential effects have caused many disasterous petroleum-product fires.

Dorn Effect

The Dorn Effect is also known as the settling potential. When a large quantity of suspended particles settles in a nonconducting fluid, a very large potential difference can be set up between the top and bottom of the container. The potential is caused by the shearing of the double layers as the particles with their layers drift slowly down through the fluid. A charge separation occurs, and because of the low conductivity of the fluid, a high potential difference is established. In time, of course, the charges drift and neutralize each other, but the rate of neutralization depends on the conductivity of the fluid. Very large potential differences have been observed in experiments conducted by the petroleum industry.

Dielectrophoresis

The dielectrophoresis phenomenon is not due to the shearing action on the Helmholtz double layer but, rather, to the action of a nonuniform field on a fluid dielectric or particles in a fluid (Refs. 13 and 26). The body force applied to the dielectric by the nonuniform field has been covered in the section on dielectric effects. Dielectrophoresis results from the motion of the dielectric fluid from the action of the field. In addition, the field can cause an induced charge distribution on any particles suspended in the fluid. This induced charge distribution results in a body force on the macroscopic particles such as was experienced by molecules. Polarization may also result from a field-induced displacement of the double layer, and thus provide a strong induced dipole. Dielectrophoresis motions tend to be relatively complex and any observations or conclusions concerning particle action must be approached with considerable caution. For example, the same field that causes a dielectrophoretic drift can also shear the double layer so that the two influences become intermixed. Dielectrophoresis can move materials in relation to each other if there is a difference in their dipole moments, either induced or natural. Action can be expected between the phases of a given fluid because the dipole moment (per unit volume) changes considerably between the liquid and vapor phases, for example.

In summary, phoresis effects generally occur from the shearing action on electrical double layers, which results in a charge separation. This charge separation can either generate a potential difference or cause the particles to drift under the influence of an external field. Dielectrophoresis results from the application of nonuniform fields and may occur without double-layer action.

ELECTROFLUID INTERACTIONS

We have reviewed the action of electric fields, dielectric action, and phoretic effects. It is now possible to go into further detail in the discussion of the more important interactions.

ELECTRIC WIND AND ION DRIFT

Electric wind is manifested by the flow of air from a highly charged needle point. The electric pinwheel utilizes the wind generated from two charged points at the ends of a pivoted arm to rotate the arm. In the vicinity of the points, a very intense electric field exists. In such a field, the surrounding gas is ionized to a high degree due primarily, to the collisions of ions and electrons with the neutral molecules. Stray ions or electrons within the gas (due to natural cosmic ray ionization, for example) may gain enough velocity between collisions to ionize the neutral molecules. The new ions are likewise accelerated by the field and tend to move away from the intense field, to a point where the field strength is lower. Here, elastic collisions occur with neutral molecules, which leads to a drifting motion of both the ions and the neutral molecules. On a macroscopic scale, this drifting is a local mass motion or wind.

When the ions and neutral molecules move away from the point of high charge, a change of momentum takes place and a reaction on the body results. This is the force that turns the electric pinwheel. This same phenomenon can produce a low velocity flow of a mass of gas by using sufficient points or a grid of fine wires, as shown in Figure 10. Such arrangements can induce fluid flow or pumping, or produce useable thrust; they form the basis for electric wind, ion drag pressure, and similar phenomena. Fundamental limitations to this type of device are the power required to achieve mass flow and the potential that can be applied before breakdown (sparking).

The action of a field on flames is distinct from the electric wind phenomena, since the ions exist in the flames and need not be generated by the field. As a consequence, the field effects on flames are the result of the motion of particles within the flame itself. Some portions of the flame contain a greater negative charge, and others contain a greater positive charge. This variation in the net charge leads to severe distortions of the flame as the field is applied (Figure 2). Tests on flames indicate a much higher degree of ionization exists in the reaction zone than is expected under equilibrium conditions (Ref. 17). Applied fields can lead not only to the distortion of the flame, but to mass motion of the air surrounding the flame. This action is a logical corollary to the electric wind. Experiments show that definite changes in heat transfer can also result (Refs. 27 and 28).

When ionization exists in a gas, the distribution of ions may be distorted even though the average charge density is zero (the mass of the fluid is electrically neutral). Since the mobility of the negative and positive ions is substantially different, an applied field

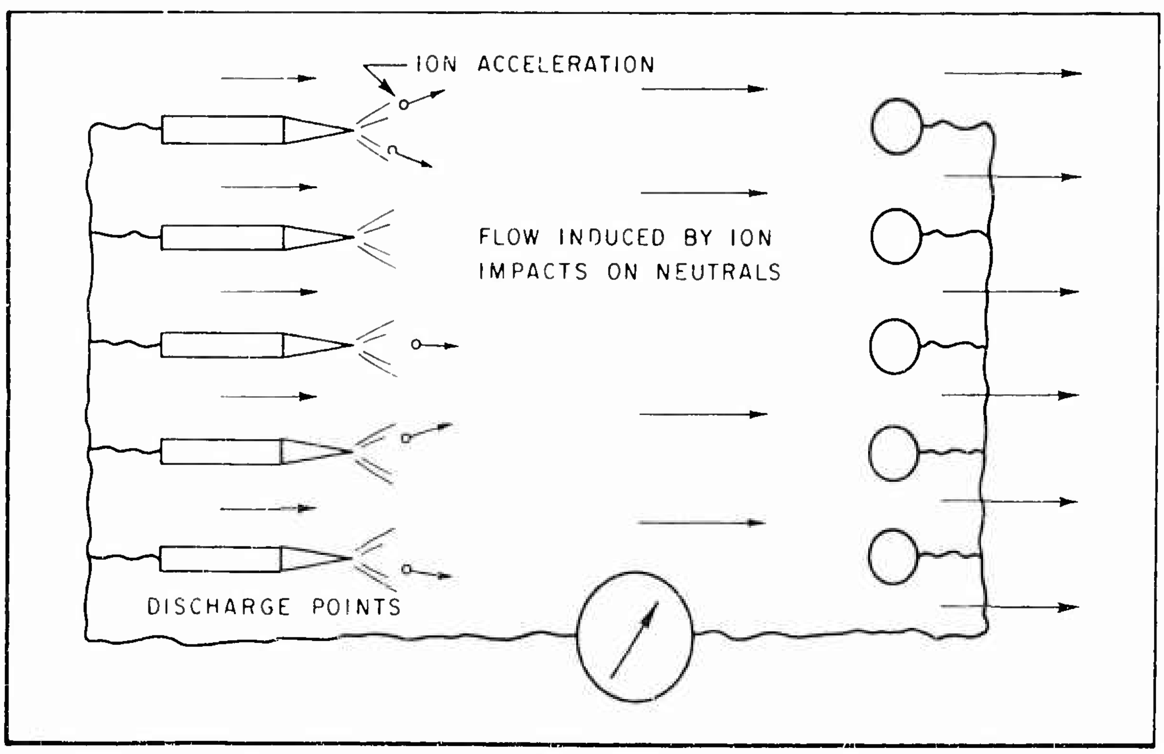


Figure 10. Induced mass flow by a grid of needles

will cause unsymmetrical motion of the ions and would likewise tend to cause slightly different mass motion of the fluid. Such action is limited by the amount of recombination taking place and the ambipolar diffusion coefficient. Ambipolar diffusion occurs as a result of the combined effects of the diffusion of a single specie and the attractive Coulomb forces of unlike charges. As the positive and negative ions move in the applied field, a charge separation occurs with a resultant attraction between the oppositely charged areas in the fluid. In addition, as the ions are separated, natural diffusion acts to return the charges to a more uniform distribution. The combined influence of diffusion and charge separation is known as ambipolar diffusion. The net result of these effects is to reduce the rate of drift and the amount of distortion produced by the field.

The most outstanding illustration of the potentially powerful influence of ion drift is Clark's experimentation (Ref. 28). This work shows that flow streams can be diverted through large angles, boundary layers and heat transfer can be influenced, and even surface erosion can be inhibited (Figures 11, 12). These experimental data indicate effects on flow quite out of proportion to results ordinarily expected by the actions of fields. They point to the importance of conducting further detailed and systematic study of the electro-fluid interactions.

A corollary to the ion drift effect is the possibility of using ion motion to generate electrical power. This possibility is based upon the inverse process of electric wind (Refs. 15, 16, and 17). In inverse electric wind, the ions are not accelerated by a given potential difference, but are slowed down by the field and return their energy to an external circuit. This purely electrical field effect does not involve external magnetic fields. References 15, 16, and 17 discuss ion-motion power generation thoroughly.

FLUID ELECTRIFICATION AND ELECTROVISCOSITY

Since the phenomenon of spray electrification has its foundation in the action of the Helmholtz double layer, the main features of this action were covered under phoresis. The charge generated in the exhaust of steam through nozzles and the spray of liquids from nozzles and from waterfalls is the result of shearing action on the double layer. Bubbles that rise to the surface of a liquid and burst lead to strong charging phenomena from the double-layer effect. Several experiments have been conducted in which fluids have been sprayed out of nozzles into regions of intense electric fields (Refs. 7, 8, and 29). The level of charging was considerably higher than that obtained by double-layer action alone. When the field was increased, the spray configuration was altered considerably, since droplet size, distribution, and charge are influenced to a large extent by the field.

The phenomenon of flow electrification was covered in considerable detail under phoresis. The shearing of the double layer builds up a large charge. A critical factor is the level of conductivity of the fluid. If the conductivity of the liquid exceeds 50×10^{-12} mhos per centimeter, the charges dissipate themselves quickly within the fluid. The hydrocarbon liquids in which charge separation takes place would be extremely poor conductors of electricity if no impurities were present. If the liquid were very pure, no charge is generated, but impurity concentrations of one part in a billion is sufficient to cause electrification. On the other hand, small amounts of certain additives in various petroleum products increase the conductivity enough to dissipate quickly any charges developed (Ref. 12). Mixtures of hydrocarbons or additions of water increase charging effects.

Figure 11. Schlieren photograph showing impingment of reducing oxy-hydrogen flame against metal plate charged with -10, 000 volts relative to burner nozzle

Figure 12. Schlieren photograph of 250°F air flow between electrically insulated metal plate and field shaping electrode with -10, 000 volts to plate and 10, 000 volts to field shaping electrode

The importance of the impurities or additives on the electric-fluid interaction is also born out by the series of experiments of Andrade and Dodd, and Dobinski (Refs. 30 and 31). Dobinski observed that viscosity changes when an electric field is applied to a flowing liquid. He deduced that the change in viscosity varies as the square of the field strength. He deduced that the effect depended upon the amount of impurities in the liquid; as the impurities were removed, the field-induced viscosity was progressively reduced to that value for the liquid without a field. Viscosity was influenced only in polar fluids. Other experimenters verified these results. Andrade and Dodd in a series of very careful tests corroborated the earlier findings of Dobinski. Viscosity increased as the square of the field strength, and the effect was most pronounced on polar molecules. With very pure fluids, no inherent increase in viscosity was apparent with the application of a field (Ref. 32). Consequently, the impurities existing in a liquid are of primary importance. These impurities affect the amount of charge build-up in flow electrification, the rate of decay of the charge in a liquid, and the viscosity of the fluid. The degree of impurity required to show these influences is very small. Ordinary commercial grade fluids contain sufficient impurities for the effects to be evident. Water, for example, has a significant influence on various nonconducting fluids, and water is present in most practical fluids.

The influences on viscosity were explained by Andrade and Dodd as being due to the accumulation of charges in the liquid. The action of the charges on a polar liquid led to clustering and, subsequently, increasing the viscosity. Thus, the characteristic distribution of charge within a field may provide a similar variation in the viscosity in the fluid. The data of Anadrade and Dodd indicate the increases in viscosity can be as high as two to one. This influence on viscosity is of great significance to the investigator of fluid behavior and heat transfer because viscosity is a primary factor in these phenomena.

DIELECTRIC EFFECTS ON FLOW AND HEAT TRANSFER

Several effects from the body force available on neutral nonconducting fluids through the use of dielectric action have been noted. Gemant reported that the surface of a liquid can be drawn upward towards a charged needle point (Ref. 24). In a series of experiments, Pohl demonstrated dielectric action by spraying liquids upward from the surface (Refs. 13 and 26). The primary purpose of Pohl's work was to use the action to separate various suspended particles from a nonconducting solution. A nonuniform field was established between an outer circular conducting wall and a fine internal wire. Applying a voltage varying from zero to 80 kilovolts across the electrodes separated the suspensoid readily. Polarization is achieved by the action of the field on the suspended particles. The charge on the particles is induced by the applied field to form a dipole. This dipole could result from either double-layer action or the movement of mobile charges in the suspensoid particle. The action requires a highly divergent field and high field strengths. The motion of the particles is independent of the direction of the field strength, as predicted by the theory of dielectric action. The action is strongest for large particles where large polar moments can be generated.

The separation depends on the difference in the dielectric constant between the solute and the solvent. For the solid particles to be moved toward and be separated at the central electrode, the solids must have a higher dielectric constant than the surrounding liquid. When the liquid has a higher dielectric constant than the suspensoid, the liquid is induced to move toward the central wire, which causes a mixing action within the fluid. In much of Pohl's work, both electrophoresis and dielectrophoresis effects occur; the results must be viewed with this factor in mind. Dielectric effects are significant and provide an effective body force within the fluid, even though their absolute magnitude is small, as shown in Figure 13.

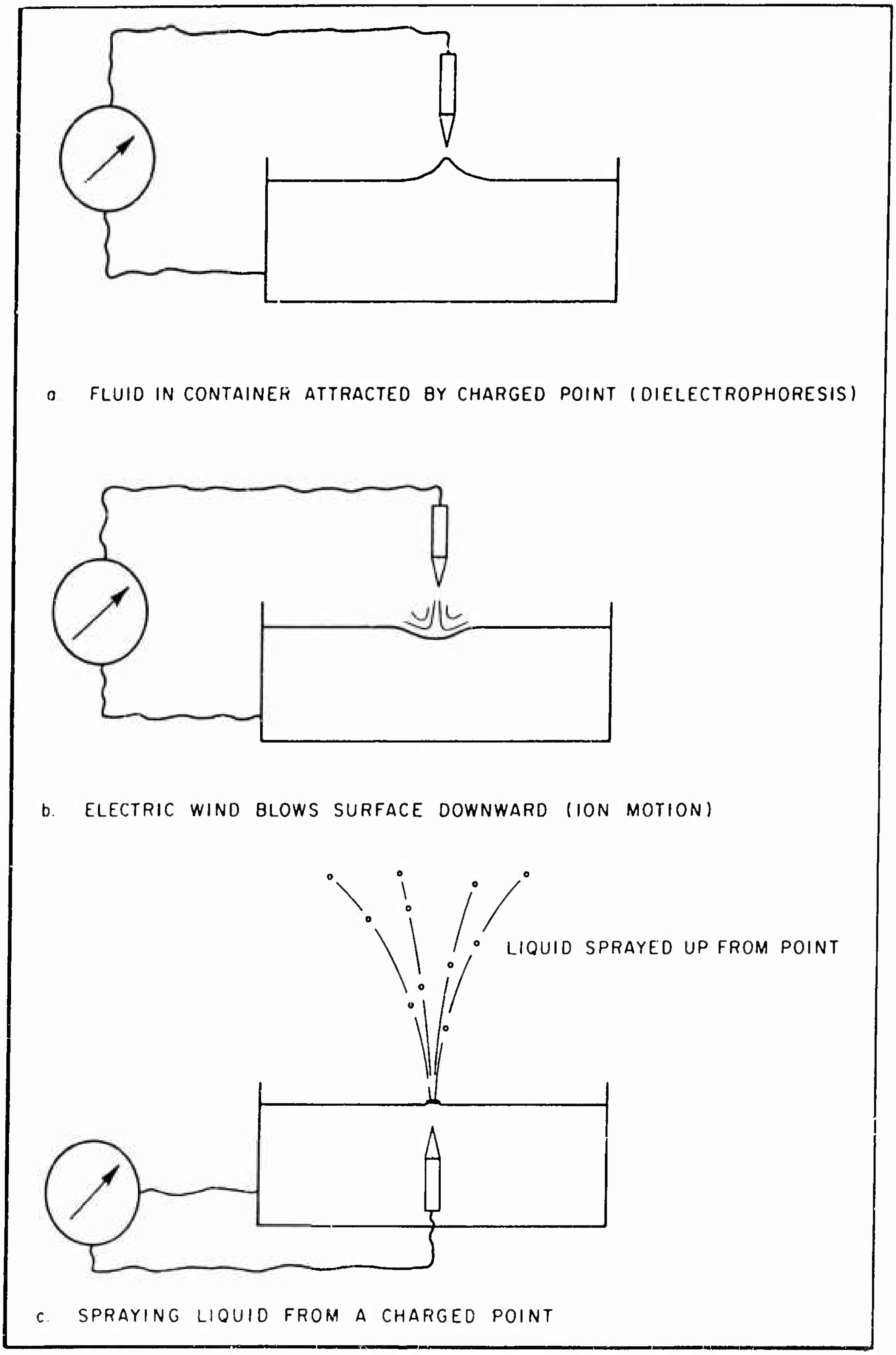


Figure 13. Electric and dielectric effects

Few experiments have been conducted on the influence of an electric field on heat transfer. The work usually has been directed at free convection in liquids, with a little exploratory work on boiling. In almost all cases, a nonuniform field was established by placing a fine central electrode in a cylindrical outer electrode. The wire was heated electrically to establish a field between the wire and the outer cylinder. Significant increases in heat transfer result; increases of over 100 percent of the heat transfer without a field have been recorded (Refs. 33, 34, 35, and 36). Senftleben studied the phenomena in gases extensively and attacked the problem on a thermodynamic basis. His analysis showed that the dielectric stress effect would be greater for a cold gas than for a hot gas, and consequently the cold gas would tend to stream toward the central electrode. This induced streaming would increase the rate of heat transfer. Although sound analyses seem to have been conducted, no electrophoretic and dielectrophoretic actions are considered. If the fluids were of very high purities, these effects could be neglected in the evaluation. Unfortunately, purity does not usually seem high enough to preclude the action of phoresis in convective heat transfer. Whether phoretic effects are present or not, strong influences on free convection appear possible. The final result may be a mixture of influences, but the net action may produce useful results. Further work in this area should logically consider the phoretic influences on heat transfer as well as other streaming phenomena induced by the field.

It is apparent that many important factors influence heat transfer and boundary layer phenomena. Although the details of all the action are not clear, sufficient knowledge exists to initiate definite explorations on heat transfer and boundary layers. Various combinations of ion drift, induced viscosity, phoretic effects, and stress-induced streaming may be used to achieve a specific result.

OTHER ELECTRIC EFFECTS

Static charging of solids is a complex phenomenon. Other aspects of the influence of fields on solids,however, will be mentioned. Mendel and Weinng found, during a series of tests, that the application of high fields to the surface of a magnesium oxide crystal produced dislocations in the crystal (Ref. 37). Two types of dislocation were found, a surface dislocation and a dislocation extending through the interior of the crystal. The dislocations were not explained, but the second type of dislocation impies strong internal field effects. More striking effects were found by Clark (Ref. 28). Surface erosion of a cartridge starter turbine was effectively inhibited by the application of a bucking voltage. Cross sections from turbines after operation showed evidence of subsurface pitting. The origin of the interior pits is not clear, but Clark hypothesized that this pitting may result from some field-solid interaction. Clark, in a further work (Ref. 38), indicated that appreciable electrical effects occurred during bubble motion and cavitation. Tests indicated that electromagnetic fields were established about the bubbles rising in a fluid. When the bubbles burst upon contact with the surface, local electromagnetic fields were induced. In the same work, fluid turbulence was also found to generate local electromagnetic fields.

APPLICATION OF ELECTRIC INTERACTIONS TO THE MECHANICS OF FLUIDS AND HEAT TRANSFER

The following section presents a broad outline of the possible ways in which the electro-fluid interactions can be utilized to influence fundamental fluid behavior.

FLUID PROPERTIES

Fundamental to any investigation of fluid behavior is the nature of the fluid properties. Important properties include viscosity, conductivity, diffusion, and compressibility. If any of these properties change, flow fields, drag, or heat transfer could change. We must therefore consider the fluid properties initially. Experimentation on viscosity of liquids by Andrade and Dodd, indicated that the viscosity of fluids of normal purity changes considerably (Ref. 31). The effects were most pronounced in polar liquids, in these tests which were limited to uniform fields. Tests by Leidenfrost and Schmidt (Ref. 36) revealed an influence on conductivity. It is expected that the influence on diffusion would be strong because of the ambipolar effects.

BOUNDARY LAYERS

Of fundamental importance to the motion of real fluids is the boundary layer existing between a moving fluid and its boundary. The boundary layer depends on viscosity, local flow velocity, surface condition, Reynolds number, and many other parameters. In ordinary applications, boundary layer is a relatively small portion of the total flow field. In the case of flow in pipes and in certain cases of external aerodynamics, however, the boundary layer can be extensive. Whenever the boundary layer is changed, the total flow field surrounding a body can be influenced significantly. As the boundary layer changes under the influence of the adverse pressure gradient in a diffuser, for example, a point is reached where the flow in the boundary layer detaches from the surface. This separation usually results in the entire flow stream separating in the diffuser. Diffuser efficiency and pressure recovery are markedly reduced by this separation. The divergence angles of conical diffusers for subsonic flow are limited to approximately 8 degrees to prevent such separation.

Boundary-layer flow is categorized as laminar and turbulent. At very low Reynold's numbers, laminar flow exists. In pipes of small diameter and low rates of flow, laminar flow exists over the entire length of the pipe. In external aerodynamics, the laminar flow exists on the leading edge of the body; as flow progresses over the body, however, a transition to turbulent flow will occur at a critical Reynolds number. Laminar flow is characterized by the smooth flow of layers of fluid, relatively low drag, and generally low heat transfer. Turbulent flow is characterized by extensive internal mixing of the various layers of the stream and generally higher drag and heat transfer rates.

All phenomena of fluid flow and heat transfer are intimately related to the boundary layer. The importance of the boundary layer has led to the use of suction in laminar flow control on aircraft and to the use of pressurized fluid injection to control the boundary layer. Such techniques have demonstrated very low net drag due to a stabilized laminar layer, or have delayed separation so as to increase stall angles and lift coefficients and reduce drag. Fluid injection into the boundary layer has been used to vary the heat transfer rates between the body of the fluid and the wall. It is a logical corollary, therefore, to inquire as to what influence the electric field may have on the boundary layer. Since several electrical interactions are possible, this question would require a rather broad systematic program of investigation. Such a program must consider (1) the type of fluids, (2) the type and degree of ionization, and (3) the type fields.

Extreme care must be exercised so that the influence can be separated. Electrophoretic and ionic influences can become intermixed. Oscillating field effects on ions and dielectrophoresis can occur in a combination.

The condition of the fluid-wall interface is of vital importance to the resistance of a moving fluid. From a macroscopic viewpoint, the velocity of a fluid drops to zero at the wall because the fluid "sticks" to the wall. The velocity then increases from the wall out to the free stream flow. Such a macroscopic viewpoint gives no insight as to the nature of the fluid-wall contact. Viewed on a kinetic theory basis, the neutral molecules strike the wall and are momentarily adsorbed at the surface of the crystal lattice. Adsorption results from the electrical forces at the molecular level (Refs. 7 and 39). The kinetic energy of the impinging molecules is given up to the wall in the process. A short interval later, these molecules acquire sufficient energy from the surface to leave the wall. Although the approaching molecules may have had a directed component of velocity (mass velocity of the flow) in addition to random motion, they leave the surface with a random orientation. The net change in momentum normal to the surface leads to the fluid exerting pressure on the wall. The net change in the tangential velocity due to adsorption at the surface leads to a frictional drag at the surface, with subsequent fluid shear. Consequently, the nature of the impact of the incident molecule and the type of reflection will influence the average flow velocity near the boundary significantly. When the density of a gas is low enough, the phenomenon of slip flow occurs. In this case slipping apparently occurs at the wall and the velocity is not completely reduced to zero at the interface.

The importance of the fluid-wall interaction on velocity and boundary layer leads one to the question of the possible influences of the electro-fluid interactions at this interface. If small body forces could be created directly at the interface, the entire boundary layer and flow field could be influenced. If highly localized interactions could be induced, then some degree of slip flow in dense gases might be possible. Such microscopic influences will require special attention as to the condition of the surface, since local irregularities or crystal imperfections could lead to relatively intense fields. If suitable field shaping were possible on a microscopic scale, some influence on the surface flow might be possible.

TRANSITION FROM LAMINAR TO TURBULENT FLOW

The transition from laminar to turbulent flow is a sensitive parameter in aerodynamics or fluid mechanics. Surface roughness, fluid properties, degree of fluid turbulence, and pressure gradient all play an important role in the onset of turbulence. The apparent natural instabilities in the boundary layer lead to roll-up and then to turbulence. If sufficient damping exists, this local turbulence can decay. Because of the sensitivity of the onset of transition, removing small amounts of fluid by suction have been successful in stabilizing the laminar layer. The very sensitivity of this instability may be an excellent area for study of electrical interactions. Field influences on the basic mechanism of transition and the possible changes to the onset of turbulence can be studied. Increased local viscosity or variable viscosity could affect the local damping in the region of initial instability. Body forces derived from any of the many electrical effects could possibly be applied to accelerate portions of the boundary layer. From the results of past porous suction tests, the magnitude of the body forces should be very small. Only careful experiments can indicate if any modification to transition can actually be achieved.

SEPARATION

Although separation is not as critical a parameter as transition, it should be studied, none the less, to determine whether any significant influences can be achieved through the action of electric fields. The approach used in considering separation must be similar to that for boundary layers. Possible effects of the field on the shape of the local velocity profile at separation and the influence on reattachment should be considered.

DRAG

External drag and internal pressure drop in a pipe result from the fluid shearing stresses at the wall. The surface shear stress is in direct proportion to the slope of the boundary-layer velocity profile at the wall. Any change to the boundary layer by an applied field will have a direct effect on the drag or the pressure drop. Any changes in boundary layer, transition, or separation can significantly affect the shearing stress, drag, and pressure drop.

HEAT TRANSFER

Forced convection depends upon the manner in which heat transfer is accomplished through the boundary layer. All studies of the boundary layer will therefore apply directly to heat transfer. Since a thermal boundary layer is established in conjunction with the velocity boundary layer, heat transfer must be examined specifically. A variation of conductivity or viscosity (Prandtl Number) of the fluid could markedly influence the temperature profile. The internal heat generated by ohmic heating within the fluid may have a significant influence.

Fluid mixing directly affects heat transfer. Mixing interchanges hot and cold slugs of fluid and greatly increases heat transfer. Such techniques as shaped fields, controlled ionization, or seeding could possibly be used to increase local mixing. It may be possible to reduce heat transfer at a wall by using similar techniques to inhibit mixing.

The work already accomplished on free convection has indicated a strong influence of divergent fields. Free convection is marked by the existence of a very small driving force. When the surface of a still fluid is heated, the heating causes the warmer, less dense fluid to rise. This local, induced convective flow adds to the pure conduction through the fluid to provide heat transfer. The driving force is the small buoyancy in the heated layer. An additional body force applied near the surface should significantly influence heat transfer; such effects have actually been observed (Refs. 34, 35, and 36).

Important areas to be studied are electro-fluid heat transfer under condition of zero gravity and multiphase fluids. Under zero gravity, no free convection can occur. Existing body forces are zero or have been cancelled by the orbital trajectory. Electric-fluid interactions could be very effective in both fluid orientation and heat transfer. The suitable interaction might move the fluid against or away from a given surface. We must have a sounder understanding of the basic interactions, however, before we can use them in actual Zero G environments.

Heat transfer in multiphase systems is complex. Boiling and condensing phenomena are usually approached on a semiempirical basis. Two-phase or multiphase flow processes also present considerable difficulty in heat transfer. The addition of electric fields to these phenomena may provide not only techniques for studying the flow and heat-transfer mechanisms, but means for directly influencing the phenomena. The key feature in phase change is the large change in volume. When a liquid changes to a vapor, many changes may occur, including: (1) a large change in the dipole moment per unit volume; (2) a change in ion drift velocity or in the damping of motions; (3) influences on bubbles from Helmholtz double-layer action; and (4) the tendency for droplets, when formed, to be ionized. All these factors provide possible means of directly influencing the mechanisms of boiling or condensing. Changes in bubble size, rate of formation and emission from the surface, as well as effects on the films and the droplets and their removal, should be studied. The most important factor in the two-phase fluid case is that a potentially large change in body force exists between the gaseous and liquid phase.

SOURCES OF IONIZATION

In the application of fields to gases, sufficient ions must be provided if ion drift interactions are to be utilized. Several possible sources of these ions exist. The combustion chambers of engines, including turbines, ramjets, rockets, and starters, provide exhaust gases with a relatively high degree of ionization. Frictional heating generates local skin temperatures on aircraft and missiles operating at high Mach numbers that are high enough to ionize a portion of the air. Since the trend for future vehicles seems to be in the direction of increasing combustion and surface temperatures, these sources may provide even greater supplies of ions in future applications. Moreover, it is in these two areas -- the combustion chamber and skin -- that electro-fluid interactions may be most significant and offer the greatest potential utility. Other possible techniques for obtaining ions include the use of ultraviolet radiation, X-rays, soft beta particles, soft alpha particles, and microwaves. Seeding the gas films with materials that are readily ionized and matched to the characteristics of the primary fluid can also be utilized with any of the basic techniques. Based on the work done so far, it is believed that the areas requiring ionization would be highly localized and relatively small.

POWER AND VOLTAGE CONSIDERATIONS

The exploration of electro-fluid interactions may require power ranging from a few volts to several kilovolts. It is anticipated that the power required will be very small. Unless an arc is formed in applying the field, the currents involved in the interactions will be very small. The tests conducted to date indicate that a few milliamperes of current may be sufficient to affect the fluid, but larger amounts may be required for conducting fluids. The power required will, of course, be directly related to the work done on the fluid and the efficiency of the process. If a mass of fluid is to be accelerated or a mass velocity is to be maintained, then power requirements may be very high, regardless of the efficiency of the process. It is expected, however, that the most important influences can be achieved by acting in small regions. We may be able to limit the electro-fluid effects to the boundary layer, to the transition zone, or to the region near the surface in convection, for example. The interactions can be used to trigger or stabilize natural flow phenomena. Control of the fluid can be achieved not by applying brute force, but rather by modifying the boundary layer, such as is done in various existing forms of boundary layer and flow control. The application of fields to such localized areas should require very small currents and, consequently, even with high potentials, the power required would be small. The nature of electrostatics usually involves very high potentials and relatively low currents.

These electrical requirements are distinct from the normal electrical circuit requirements. Electrostatic generators rather than electromagnetic generators are required. In electrostatics, it is relatively simple to produce potentials of thousands or even hundreds of thousands of volts but with very small currents. Small laboratory generators weighing just a few pounds readily produce potentials of this order, but it is doubtful that they can be used for practical applications. Other sources of potential may be inherent in the flow system. Charge was found to be generated in flow of fluids through pipes and nozzles and during bubbling and settling, for example. Charge exists in aircraft static charging and in the operation of a helicopter rotor. Recorded data indicate potentials up to hundreds of thousands of volts.

From such system-developed voltages two separate possibilities exist:

1. The natural charging phenomena may be used as a source of the desired potential. These high charges may be directed through suitable conductors to local areas of application. Considerable difficulty will undoubtedly be encountered in attempting to utilize these potentials, but we believe the concept is worthy of some consideration.

2. The converse possibility is also of fundamental importance. If large charges are generated by the over-all system (flow through a network of pipes, airflow over an aircraft, etc.) then very high local fields may exist in small areas within the system. Such fields may interact within the fluid system in an uncontrolled manner and may also affect the measurements of basic phenomena. A field-solid interaction may also take place. Intense fields would tend to localize in areas of discontinuity within the structure. It is of interest to note that the macroscopic phenomena of fretting, fatigue, and failure usually occur at such discontinuities. Although it is almost pure conjecture that fields could significantly influence these phenomena, the possibility must be considered in any over-all discussion of the electric field interactions.

SUMMARY AND CONCLUSIONS

Interactions of electric fields with fluids have been reviewed, including the observed effects and the possible mechanisms of electric action. The many possible interactions include:

1. Ion drift due to the field
2. Charged particle motion in AC fields
3. Phoresis action
4. Dielectrophoresis
5. Changes in fluid properties

Many uncorrelated observations have been made, all of which contribute to the over-all understanding of the interactions. These field actions apparently have not been studied systematically, however, and some of the past observations may include a combination of effects. The body forces due to the electric fields appear to be of sufficient magnitude to significantly and sometimes surprisingly influence gas or liquid streams. The area of greatest interest in future exploration would appear to lie in the application of fields to boundary layers.

As a result of the over-all survey conducted on electric-fluid interactions, it is concluded that when suitable electrostatic fields are applied:

1. Body forces are created in partially ionized gases.
2. Body forces are created in neutral nonionized fluids.
3. Fluid properties, i.e., viscosity, are modified.
4. Two or more interactions may occur simultaneously.
5. Fluid separations can be achieved.
6. Change of phase can be affected.
7. Heat transfer can be modified.
8. Flow streams can be turned.
9. Boundary layers can be modified.

Specific practical applications of electrofluidmechanics are not included because the control of the basic actions must be achieved first. Typical applications could include laminar flow control, heat transfer control, and drag reduction.

APPENDIX

OTHER CONSIDERATIONS

The scope of the review and study presented in the body of this report is necessarily limited. Many other areas of electric-fluid interactions are suggested and some may be worthy of further study. No attempt has been made to indicate the relative magnitude of potential effects. The following areas, however, are indicated as meriting further study:

1. Electric field interactions with:

   a. Shock waves of all types,

   b. Acoustical waves,

   c. Chemical reactions, and

   d. Frozen flow.

2. Electric field interactions due to:

   a. Electrets, and

   b. Resonant phenomena of particles, both

      (1) Microwave and

      (2) Radio frequency.

3. A theoretical approach based upon the thermodynamics of the electric-fluid interactions. New directions of study could come from such an approach. (Some work has been done in this field, but specific attention should be given to the fluid mechanics aspects rather than to chemical aspects. Reference 40 presents an analytical treatment based on electrostriction effects.)

4. Pure magnetic field interactions with fluids.

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Unclassified Report

The possible interactions between electric fields and fluids are reviewed. Many actions are found to exist, and the basis for many of the actions is discussed. The study indicates that a wide range of electrofluidmechanic phenomena have actually

(over)

been observed. A significant body force can be exerted on either an ionized fluid or a neutral nonionized fluid. Since the application of electric fields to fluids may strongly affect heat transfer or the fluid boundary layer, the field of electro-fluidmechanics may take its place with magneto-hydrodynamics as an important physical phenomena.

1. Electrostatic Fields
2. Fluid Mechanics
3. Heat Transfer
4. Hydrodynamics
5. Boundary Layer

I. AFSC Project 5141
II. Henry R. Velkoff
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Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio.
Rpt No. ASD-TR-61-642. ELECTROFLUID-MECHANICS: A STUDY OF ELECTROKINETIC ACTIONS IN FLUIDS. February 1962, 51 p. incl illus and tables.

Unclassified Report

The possible interactions between electric fields and fluids are reviewed. Many actions are found to exist, and the basis for many of the actions is discussed. The study indicates that a wide range of electrofluidmechanic phenomena have actually

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been observed. A significant body force can be exerted on either an ionized fluid or a neutral nonionized fluid. Since the application of electric fields to fluids may strongly affect heat transfer or the fluid boundary layer, the field of electro-fluidmechanics may take its place with magneto-hydrodynamics as an important physical phenomena.

1. Electrostatic Fields
2. Fluid Mechanics
3. Heat Transfer
4. Hydrodynamics
5. Boundary Layer

I. AFSC Project 5141
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